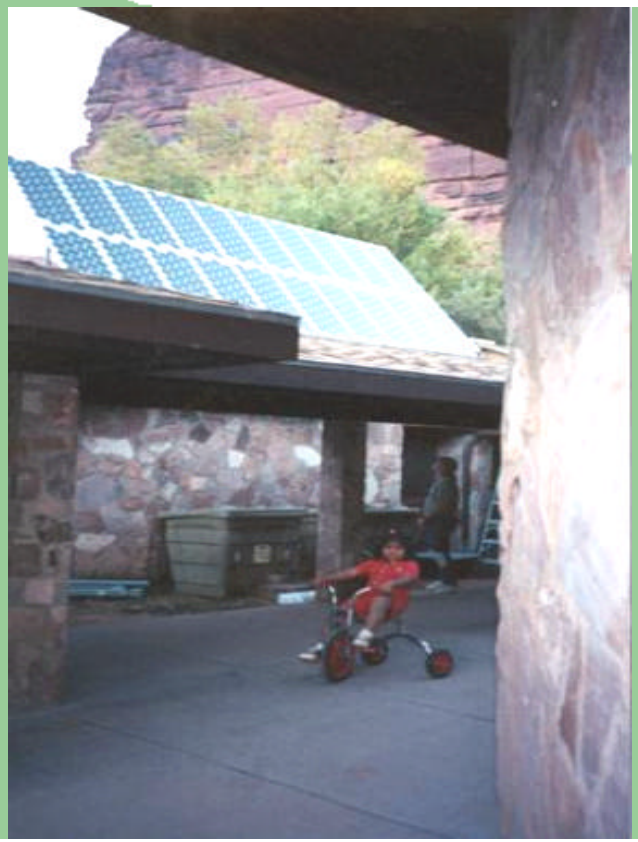
Innovation in Photovoltaic Technology



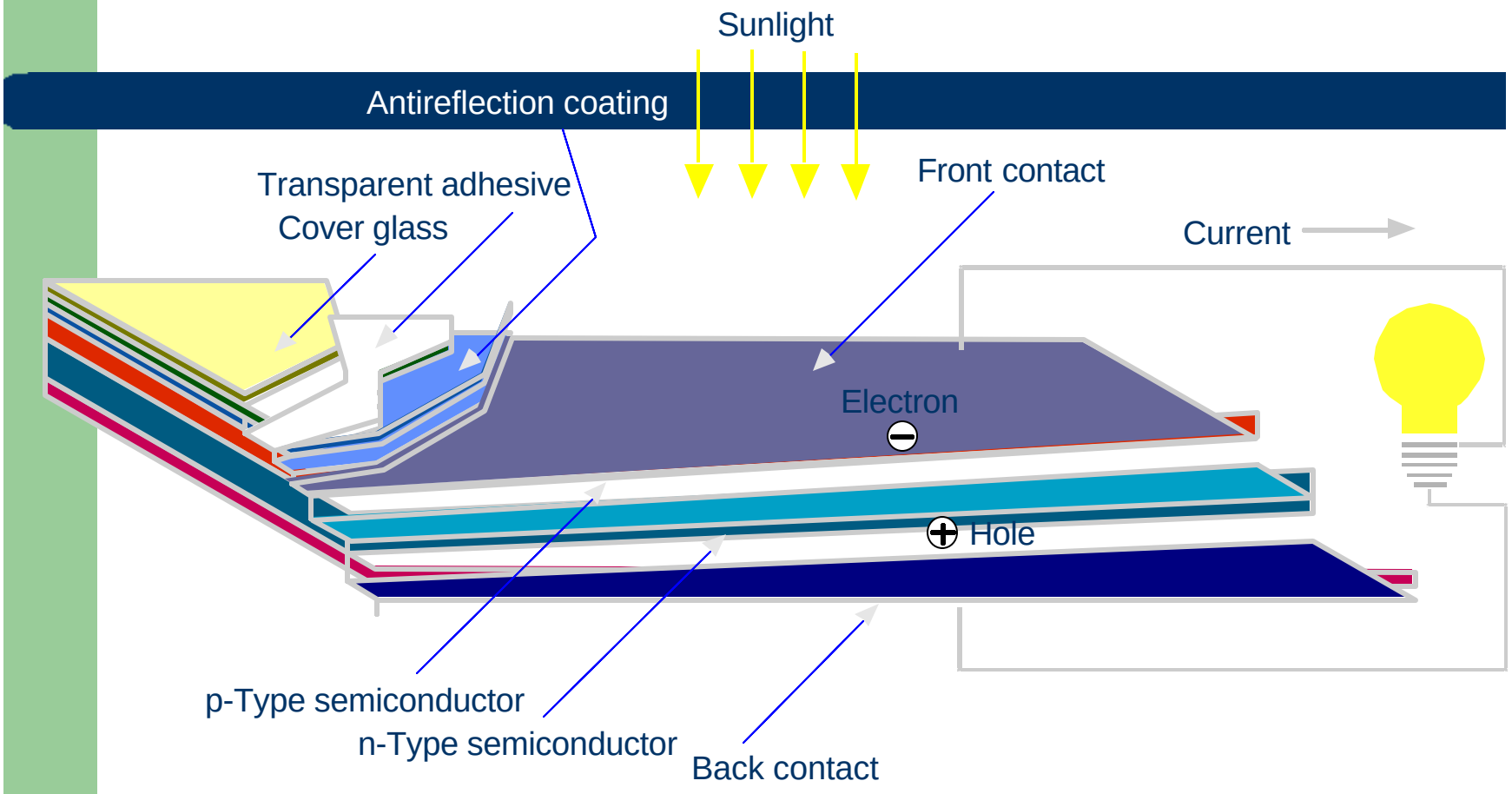
Nancy Carlisle, NREL
June 8, 2001

What is Photovoltaics?

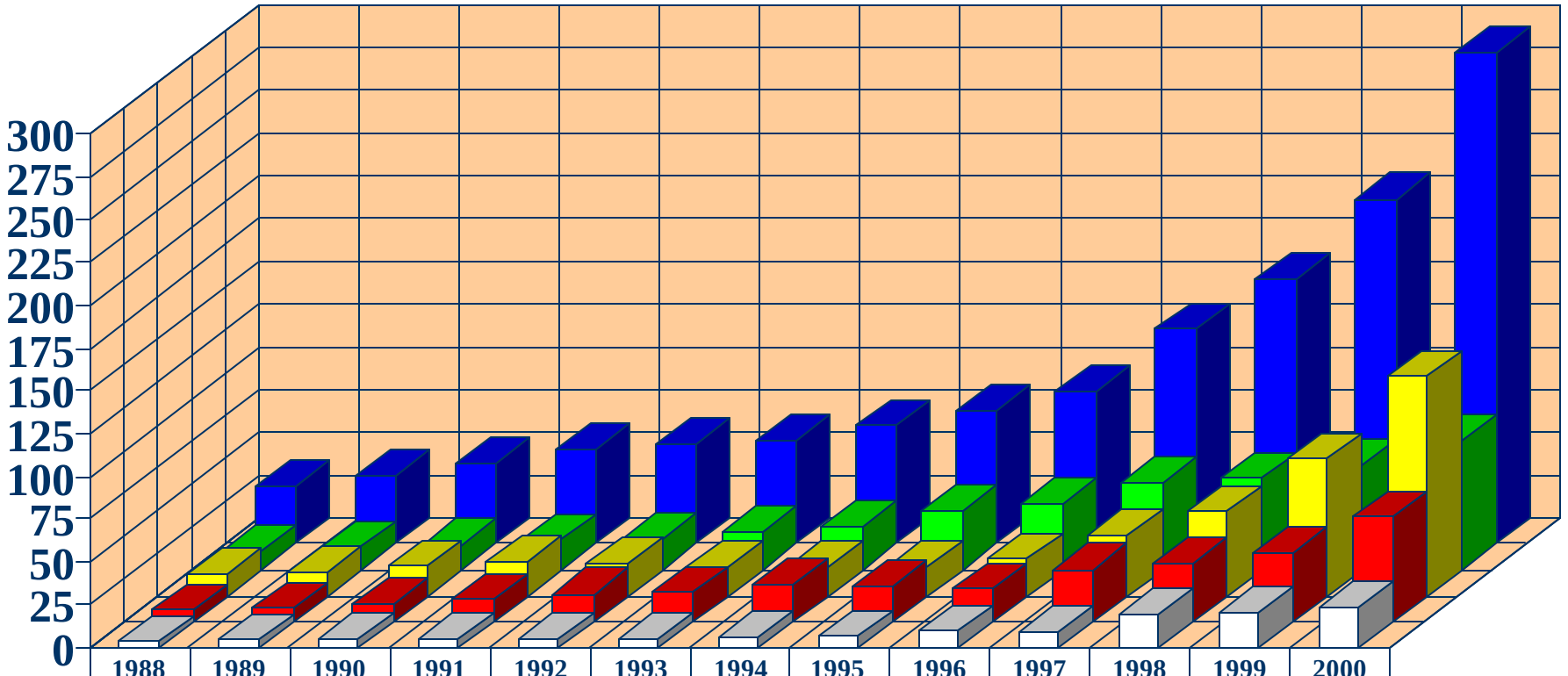
- Photovoltaics is a solid-state technology that converts solar radiation directly into direct current (DC) electricity

  - Durable: It requires no moving parts; 25 yr power warranty
  - Renewable: It requires only the sun as fuel; runs on daylight
  - Zero Emissions: It creates virtually no pollutants over its life cycle
  - Material Intensity: Silicon is an abundant material.
  - Recycling: Solar-grade silicon is electronics industry scrap
  - Energy Intensity: 1-4 Yr Energy Payback vs. Infinite for Fossil

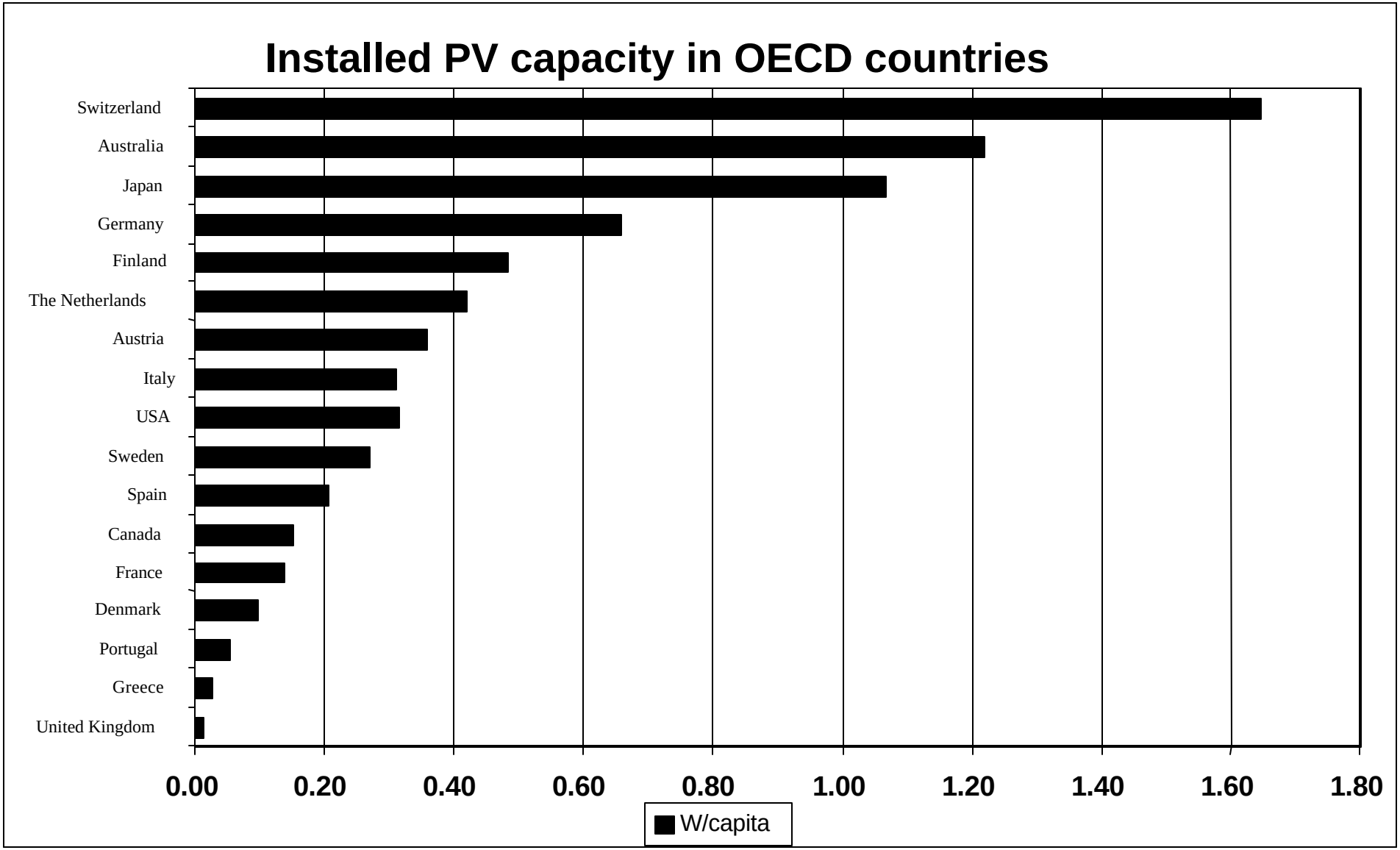
PV Cell - Cross-sectional View



Megawatts of PV Cell/Module Production 1988-2000

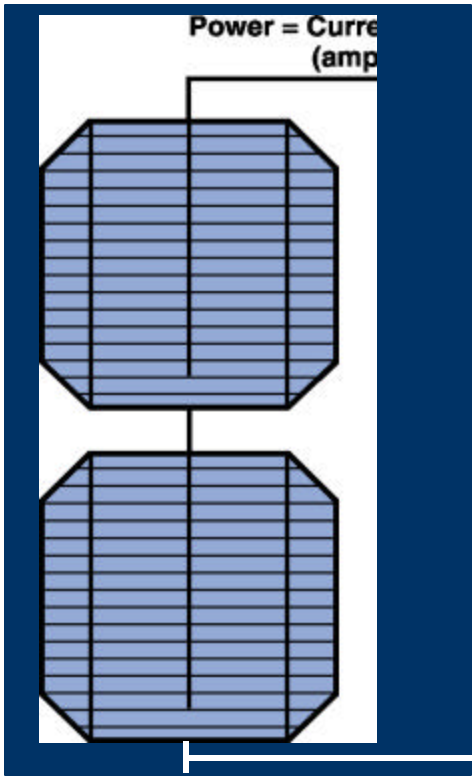


	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Rest of World	3	4	4.7	5	4.6	4.4	5.6	6.35	9.75	9.4	18.7	20.5	23.42
Europe	6.7	7.9	10.2	13.4	16.4	16.55	21.7	20.1	18.8	30.4	33.5	40	60.66
Japan	12.8	14.2	16.8	19.9	18.8	16.7	16.5	16.4	21.2	35	49	80	128.6
United States	11.1	14.1	14.8	17.1	18.1	22.44	25.64	34.75	38.85	51	53.7	60.8	74.97
Total	33.6	40.2	46.5	55.4	57.9	60.09	69.44	77.6	88.6	125.8	154.9	201.3	287.65

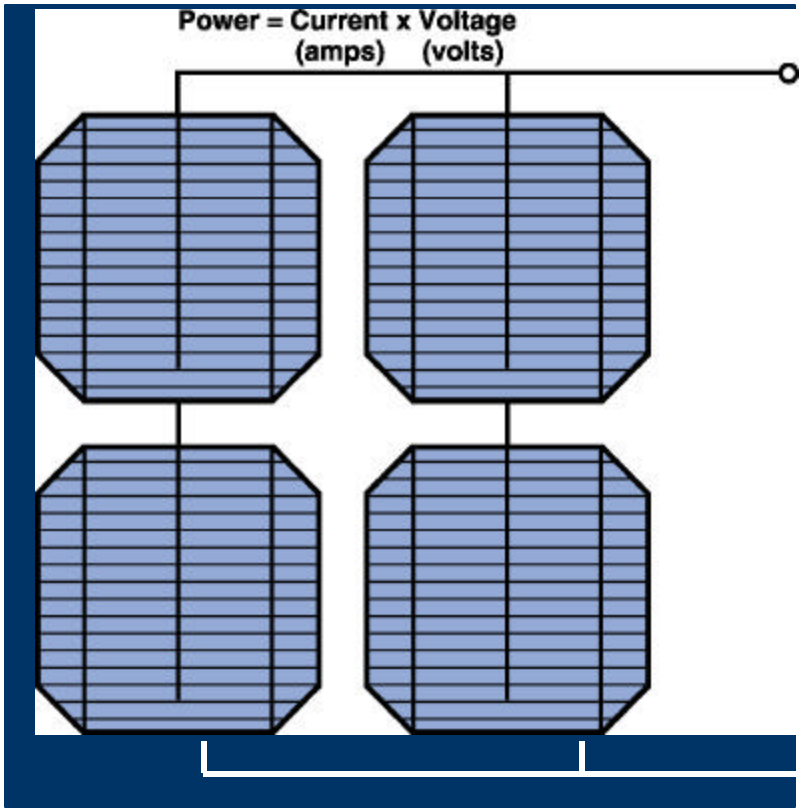

Installed PV capacity in OECD countries
Switzerland
Australia
Japan
Germany
Finland
The Netherlands
Austria
Italy
USA
Sweden
Spain
Canada
France
Denmark
Portugal
Greece
United Kingdom
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
W/capita

PV Cells

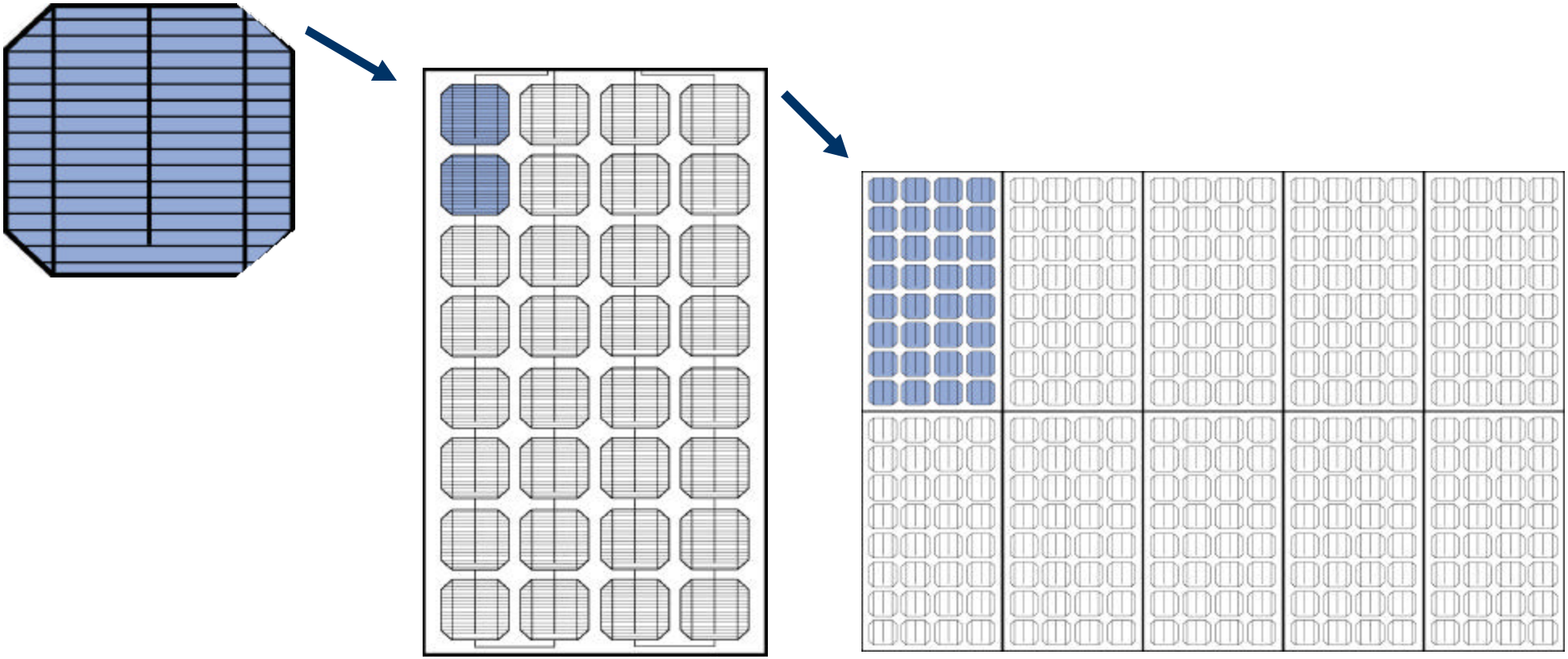
PV Cells are wired in series to increase voltage...



and in parallel to increase current



PV is Modular

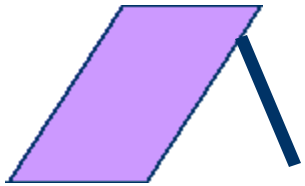


ells are assembled into modules... and modules into arrays.

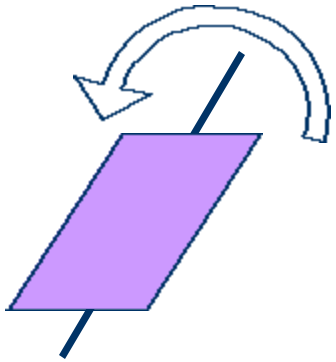
Types of PV Arrays

- **Fixed**
  - Remote
  - Building-integrated
- **Tracking**
  - single axis
  - double axis

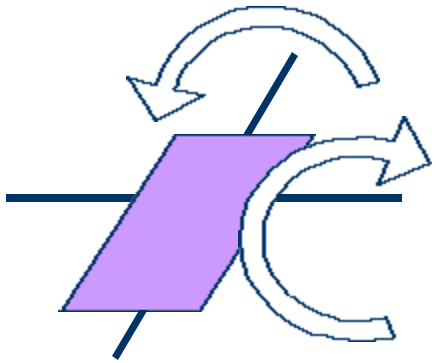
Fixed Tilt and Tracking



- Fixed Tilt Facing South

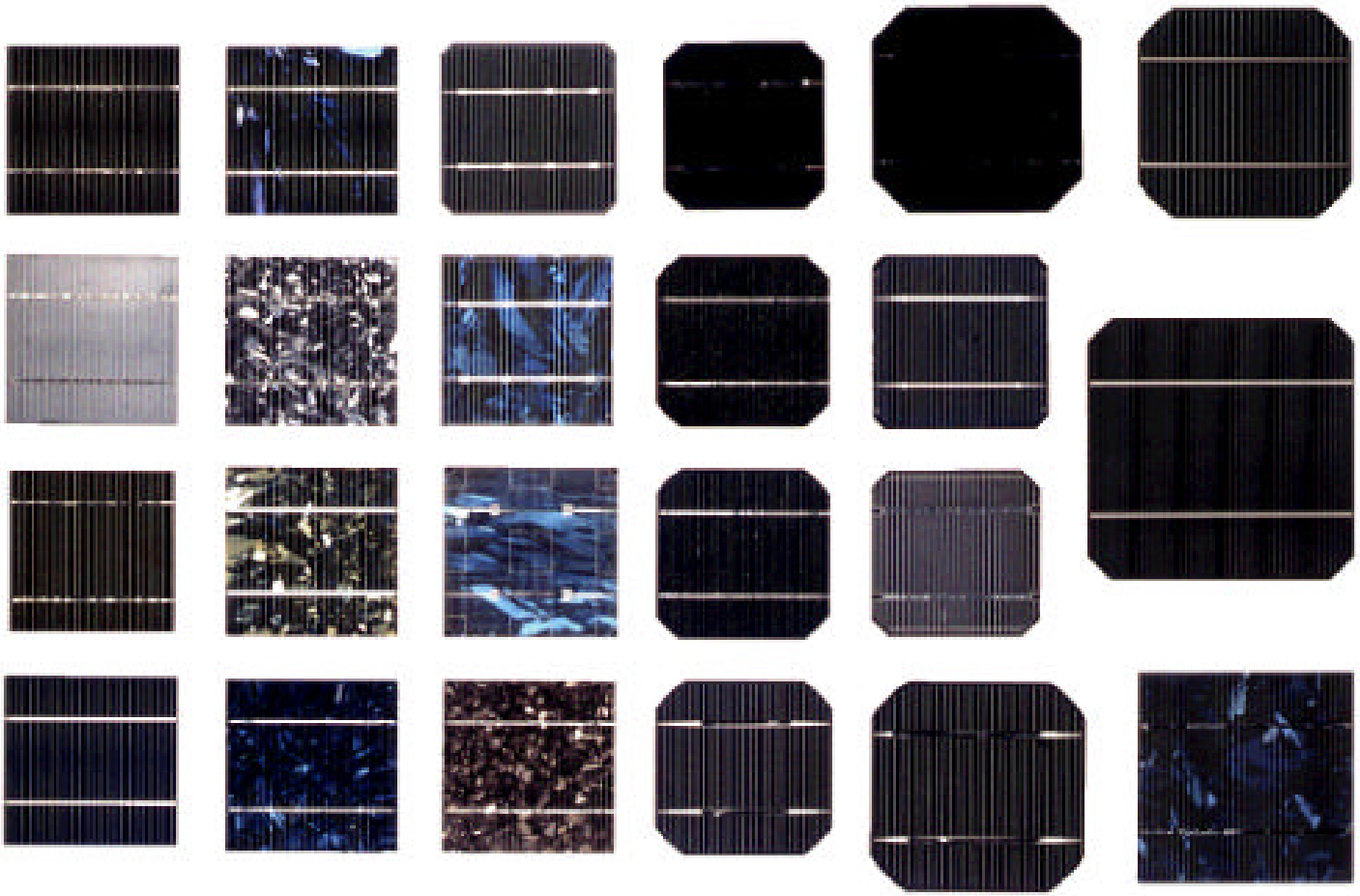


- One Axis Tracking around North-South axis tilted up from horizontal, follows sun azimuth



- Two Axis Tracking both azimuth and altitude of sun around two axes

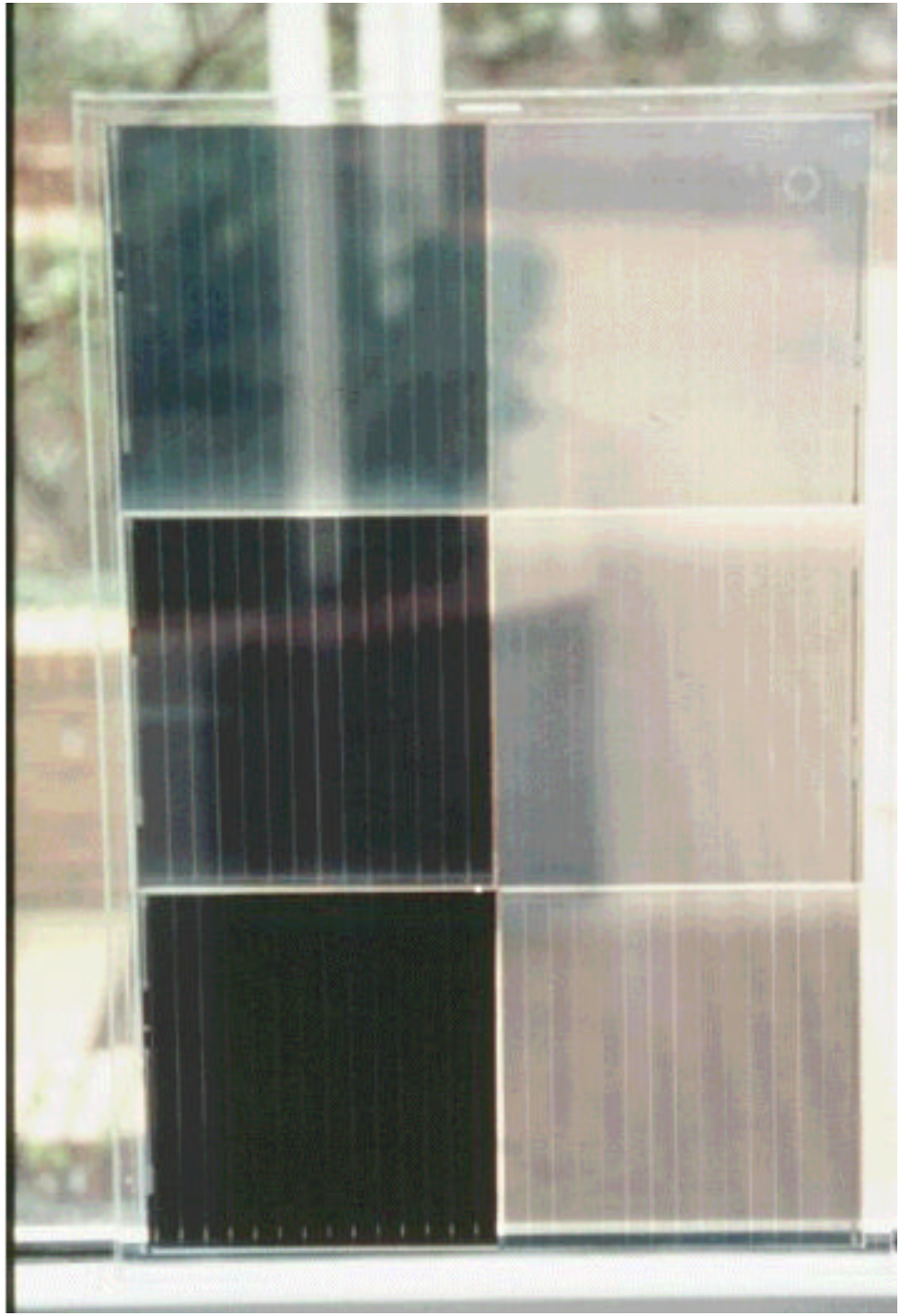
Cystalline Silicon

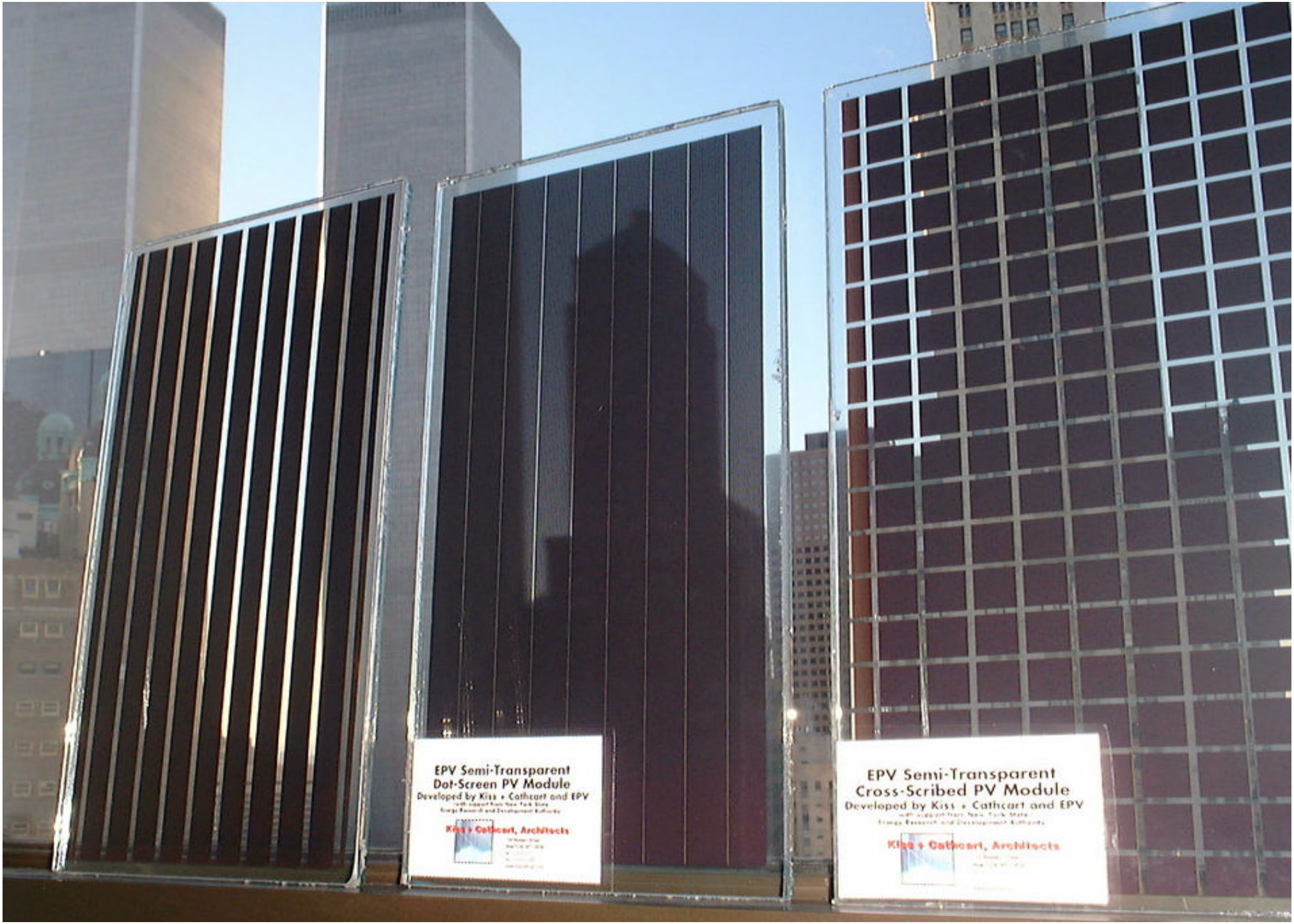


Thin Film Technology

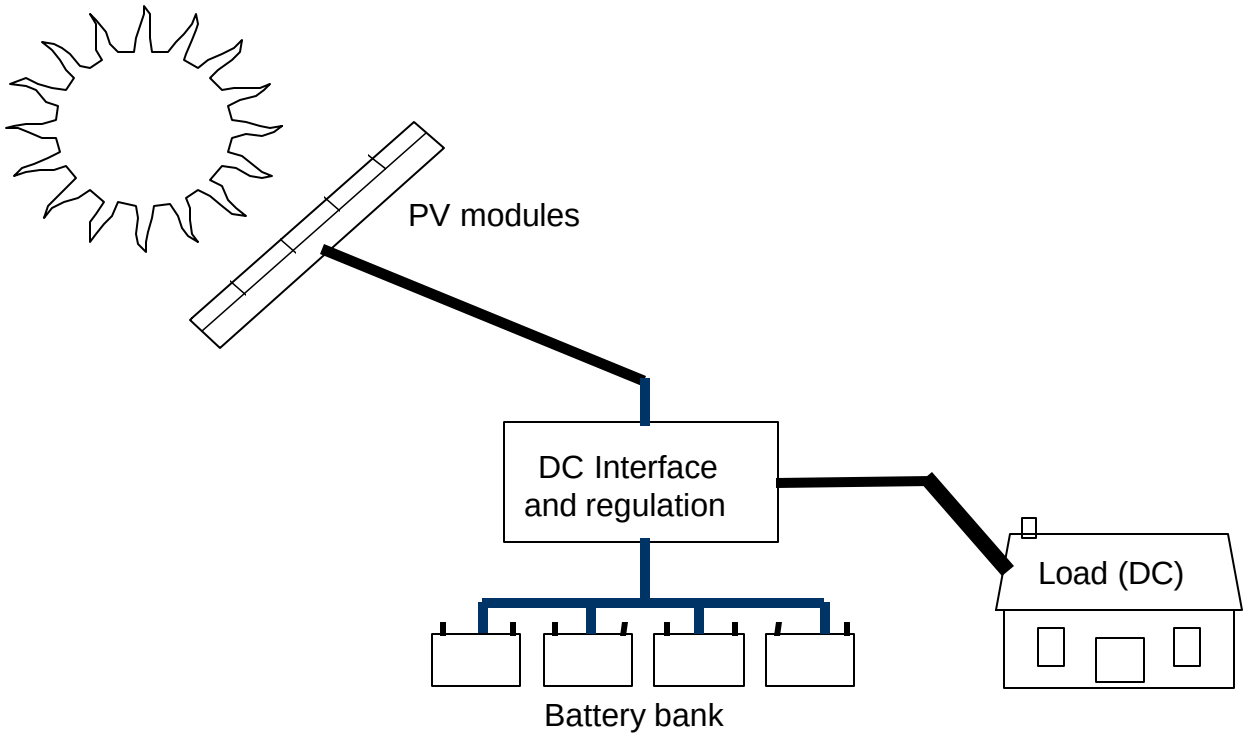
- Amorphous Silicon (a-Si)
- Cadmium Telluride (CdTe)
- Copper Indium Diselenide (CuInSe or CIS)

- Various levels of light transmission
- Etching available



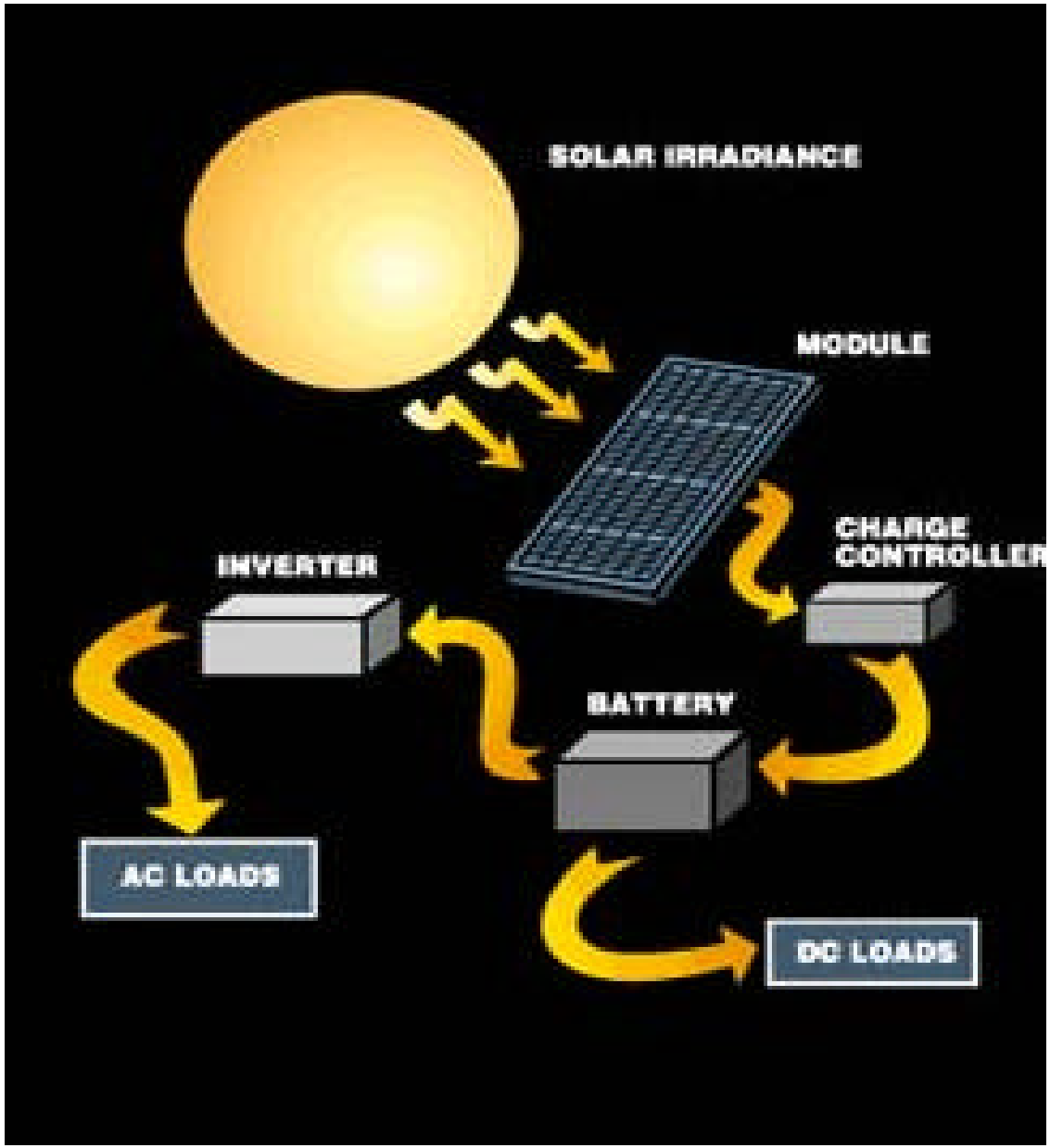

EPV Semi-Transparent
Dot-Screen PV Module
Developed by Kiss + Cathcart and EPV
Kiss + Cathcart, Architects
EPV Semi-Transparent
Cross-Scribed PV Module
Developed by Kiss + Cathcart and EPV
Kiss + Cathcart, Architects

Simple Direct-Current System



Types of Photovoltaic Power Generator Configurations

- Utility Inter-connected System
- PV Integrated into UPS system
- Small Stand-Alone DC System
- Stand-Alone AC-DC System
- Stand-Alone AC Battery System
- Hybrid Generator Combination:
  PV, Wind,
  Propane, Diesel,
  Battery Bank



Inverter Technology

- Central Inverter
- Master Slave Configuration
- String Inverter
- AC Micro-Inverter
- Cell Inverter

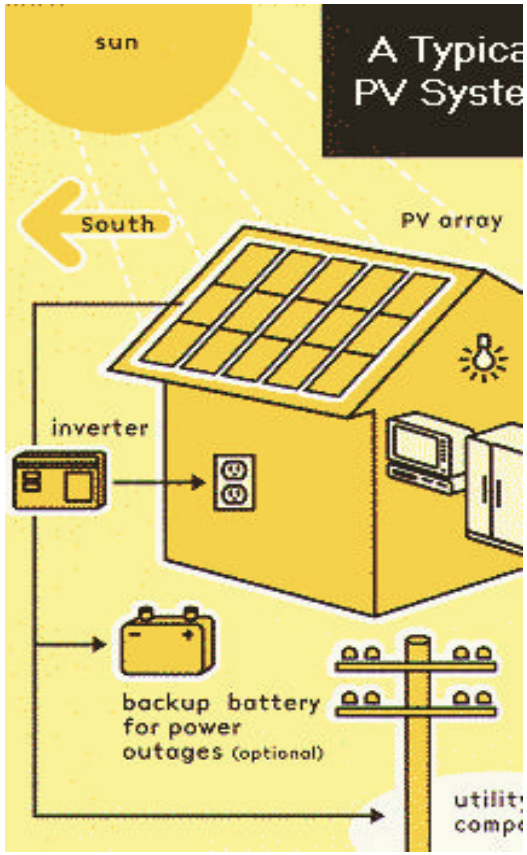
PV/Propane Hybrid Example: Joshua Tree National Park

- **20.5 kW PV Array**
- **613 kWh battery bank**
- **35 kW propane generator**
- **$273,000 cost financed by Southern California Edison under 15 year tariff**

NREL: PV and Passive Solar

System Sizing and Design

- Pre-design tradeoffs
- Load calculation
- Evaluate efficiency options
- Solar resource assessment
- Rough system sizing
- Components selection
- Performance prediction
- Final system design & cost estimation
  - Specification preparation
  - Prepackaged versus custom design



How much PV do I need?

Electricity Consumption

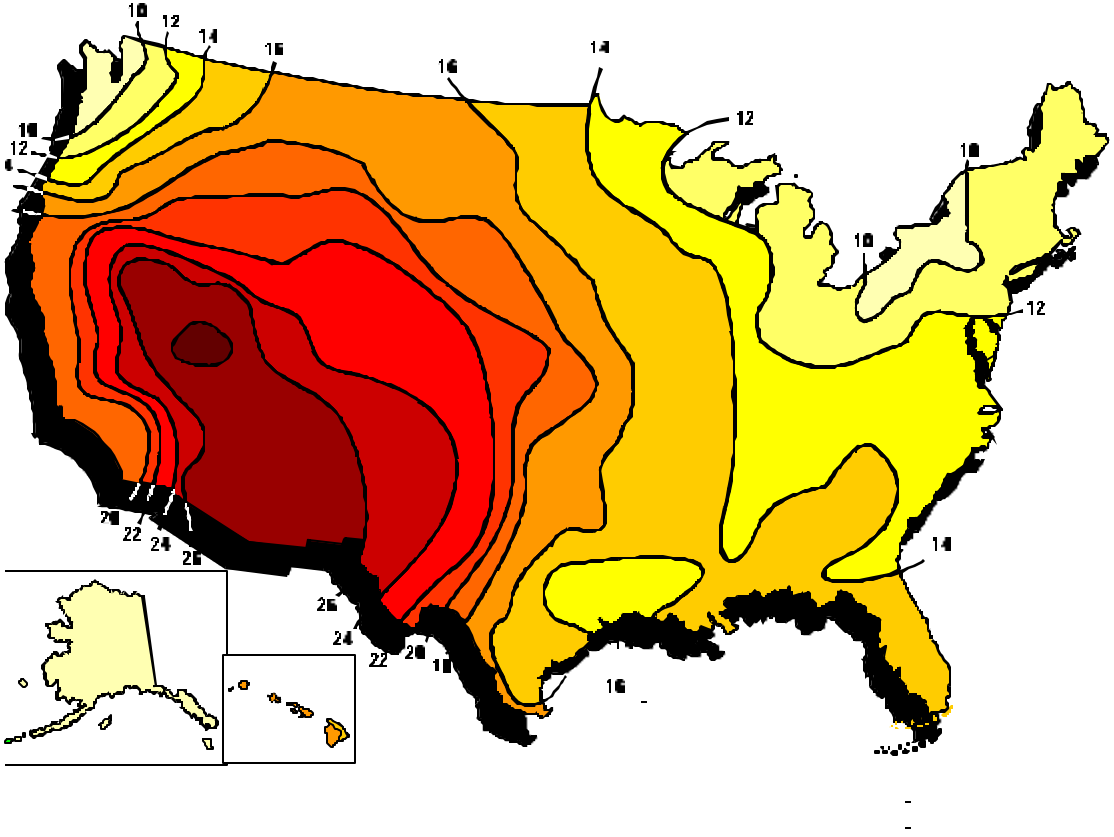
Match PV production to your electric consumption. Size your PV system to produce 100% of your electricity or a smaller percentage.

Available Space for Array

Match PV array size to your roof space. You may be surprised how much or how little your south-facing roof gets full sun all day. Trees, chimneys, vents and other buildings can block the sun or make array installation difficult.

The Budget

Match your PV system cost to your budget. PV modules are about half the system cost. Combiner box, power center, controller, inverter, battery bank, wiring



mJ/m²/d	kWh/m²/d	Btu/ft²/d
10 12 MJ/m²	2.8 - 3.3	875 - 1050
12-14 MJ/m²	3.3 - 3.8	1050 - 1225
14-16 MJ/m²	3.8 - 4.4	1225 - 1400
16-18 MJ/m²	4.4 - 5.0	1400 - 1575
18-20 MJ/m²	5.0 - 5.6	1575 1750
20-22 MJ/m²	5.6 - 6.1	1750 1925
22-24 MJ/m²	6.1 - 6.7	1925 - 2100
24-26 MJ/m²	6.7 - 7.2	2100 - 2275
26-28 MJ/m²	7.2 - 7.0	2275 2450
>28 MJ/m²	>7.8	>2450

Solar Energy Resource

Annual Average Daily Horizontal Solar Radiation

Solar Insolation

Location	I Max	I Ave
Honolulu, HI	6.5	5.5
Hilo, HI	5.2	4.8
Kahului, HI	6.3	5.8
Las Vegas, NV	7.4	6.5
Boston, MA	5.6	4.6
Denver, CO	6.1	5.5
Jacksonville, FL	6.1	4.9
Sacramento, CA	7.2	5.5
Seattle, WA	5.7	3.7
Washington, DC	5.7	4.7

(kWh/m2/day = sun hours/day)

www.nrel.gov

PV Design Tools

- System Sizing
- System Configuration
- On grid vs. Off grid
- Est. Power Output
- Building Simulations
- Shading
- Temperature & Thermal Performance
- Economic Analysis
- Avoided Emissions
- Building Energy Load Analysis
- Meteorological Data
- Library of Modules, Batteries & Inverters

Available Software

- PVSYST
- PV DESIGN PRO
- WATSUN PV
- PV CAD
- PV FORM
- BLCC
- HOMER
- ENERGY-10
- AWNSHADE

PV Design Tools

- **DOE Building Energy Software Tools Directory:**
  - **Energy Simulation Tools**
    http:// www.eren.doe.gov/buildings/tools_directory
- **UCLA Schools of Arts and Architecture:**
  - **Energy Tools Design Directory**
    http://www.aud.ucla.edu/energy-design-tools
- **Seattle Energy Works**
  - **http://www.energysoftware.com**

economics

Installed Average Cost

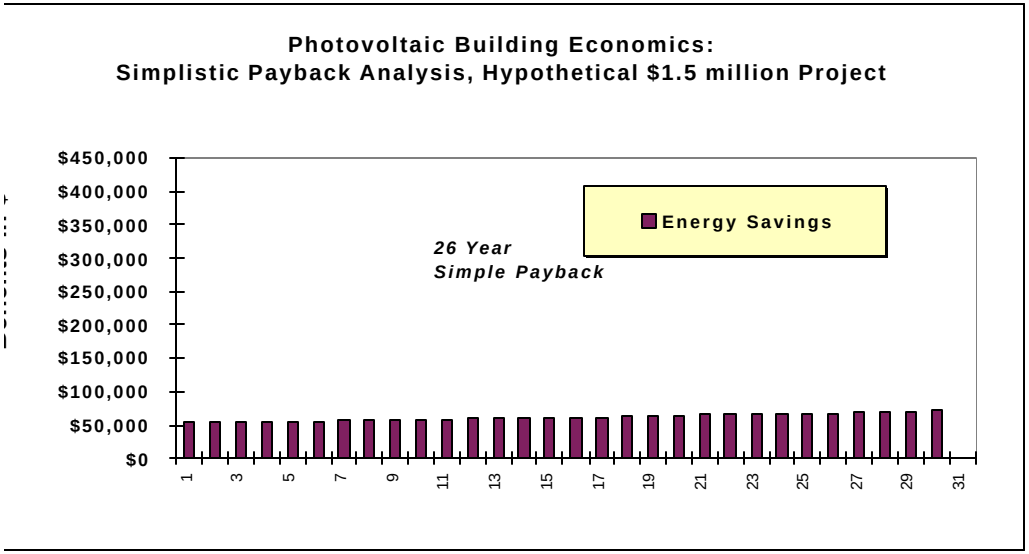
- **$100/watt 1970s**
- **$20/watt 1984**
- **$12/watt 1990**
- **$6-$8/watt 2000**

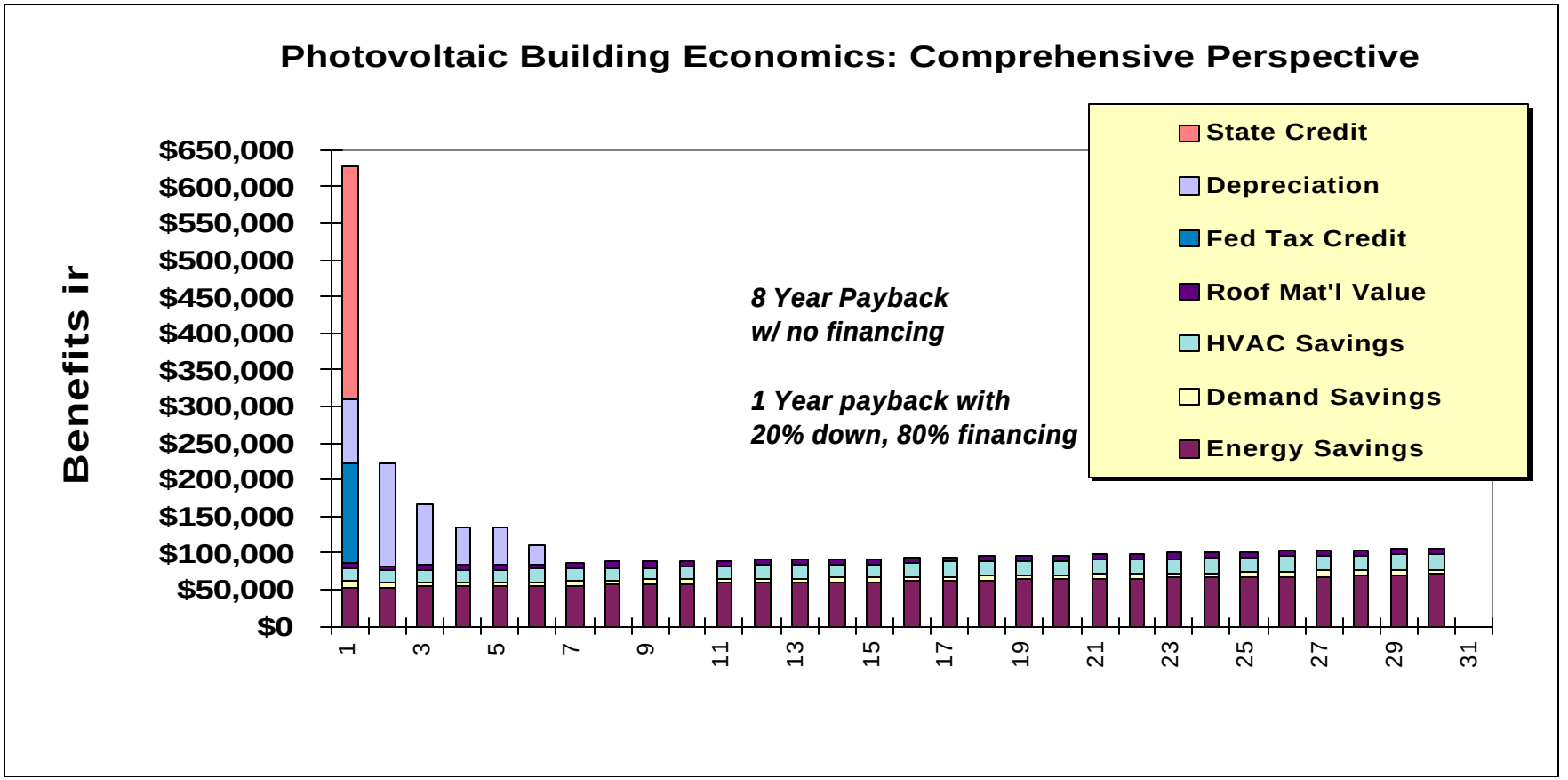
- Combine Incentives
  - **Net Metering: Utility compensation for electricity at retail rates or avoided costs**
  - **Tax Credits**
    - **State and/or Federal**
  - **Low Interest Financing**
  - **Leasing or purchasing green power from host system**
  - **State Buy-downs/rebates**
  - **Utility Incentive Programs**
  - **Economies of Scale (100kW+)**

economics

- **Costs**
  - **Design**
  - **PV laminates**
  - **Inverter (s)**
  - **BOS**
  - **Installation**
  - **Interconnection**
  - **Battery Storage**

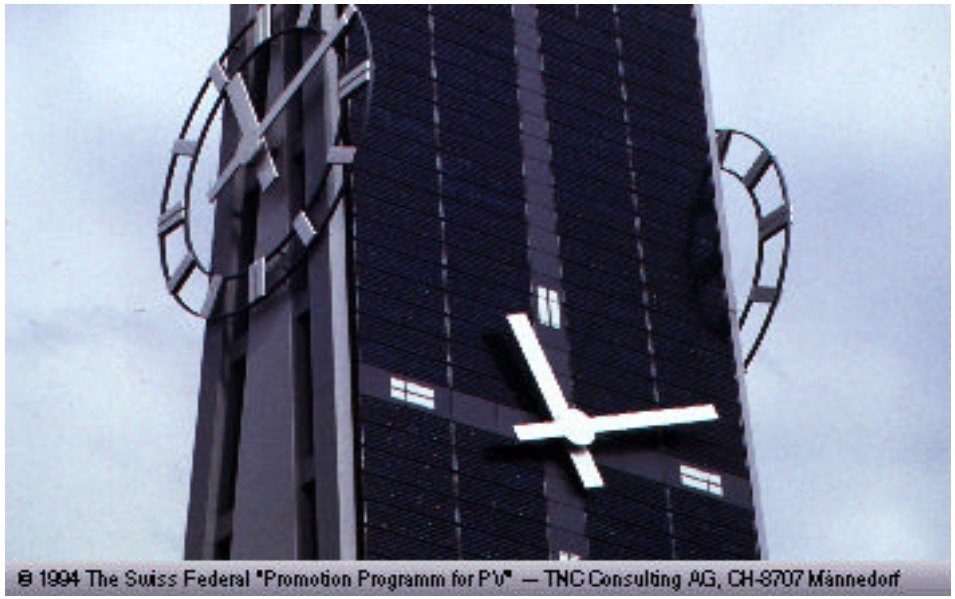
- **Benefits**
  - Electricity
  - Avoided Environmental Emissions
  - Reliable Power linked with UPS system
  - Thermal Energy Benefits
  - Public Relations Benefits
  - Construction Material Replacement Value


Photovoltaic Building Economics:
Simplistic Payback Analysis, Hypothetical $1.5 million Project
$450,000
$400,000
$350,000
$300,000
$250,000
$200,000
$150,000
$100,000
$50,000
$0
Energy Savings
26 Year
Simple Payback
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31


Photovoltaic Building Economics: Comprehensive Perspective
Benefits ir
$650,000
$600,000
$550,000
$500,000
$450,000
$400,000
$350,000
$300,000
$250,000
$200,000
$150,000
$100,000
$50,000
$0
8 Year Payback
w/ no financing
1 Year payback with
20% down, 80% financing
State Credit
Depreciation
Fed Tax Credit
Roof Mat'l Value
HVAC Savings
Demand Savings
Energy Savings
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31

Warranties

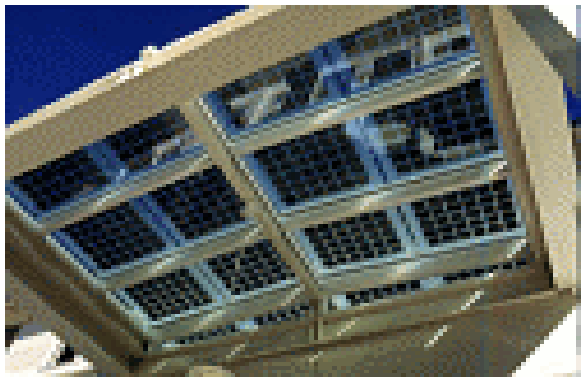
- Inverter 5 years
- Modules 20-25 years
  - Power production
- Systems 12 months
  - Extended warranties optional (e.g. 5 years)



DC PV System Example: PJKK Federal Building, HI

- 2 solar panels per lamp with peak output of 96 watts
- 39 Watt fluorescent lamps, 2500 lumens
- 90 amp-hour battery powers 12 hours per night
- ~$2500 per light

Utility-Connected PV Example: Presidio Thoreau Center



- Building-Integrated Photovoltaics
- 1.25 kW PV Array
- Spacing between cells admits daylight into entry atrium below

Summary

- There are many innovative examples of BIPV in architecture today
- The costs have dropped dramatically
- BIPV offers imaginative solutions, as one part of a renewable portfolio of solutions, to our energy problems